Pressure Dependence of Magnetoresistance for Fe/Cr Multilayers

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Pressure Dependence of Magnetoresistance for Fe/Cr Multilayers

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The magnetoresistance (MR) in Fe/Cr magnetic multilayers (MML) has been measured under high pressure up to 2.5 GPa. It is found that the spin-dependent scattering plays an important role in the pressure dependence of MR ratio. In the present work, for [Fe(20 Å)/Cr(10 Å)]$_{20}$ MML with antiferromagnetic (AF) state, the pressure coefficient of saturation field H_s is $(1/H_s)(\partial H_s/\partial P) = 3.3 \times 10^{-2}$ GPa^{-1} between 0.1 and 2.5 GPa. We found that the $(1/|J|)(\partial|J|/\partial P)$ for AF-Fe/Cr MML with polycrystalline structure is opposite in sign to that with epitaxial one. For [Fe(20 Å)/Cr(22 Å)]$_{20}$ MML with ferromagnetic (F) state, anisotropic magnetoresistance (AMR) decreases with increasing pressure. It is suggested that the anisotropy constant decreases with weakening spin-orbit interaction at high pressure. At high field, the AMR is easily suppressed by applying pressure while the giant magnetoresistance around H_s increases slightly with increasing pressure for polycrystalline Fe/Cr MML.

Index Terms—**Giant magnetoresistance, multilayers, pressure effects, superlattices, thin films.**

I. INTRODUCTION

THE electronic properties of magnetic multilayers (MMLs) have attracted much interest because of their fascinating phenomena since the giant magnetoresistance (GMR) in Fe/Cr MML was discovered by Baibich *et al.* [1]. The most noticeable properties for these MMLs are antiparallel coupling of the ferromagnetic layers for particular thickness of the nonmagnetic spacers [1]–[5]. Previously the temperature and magnetic field dependences of the resistivity of Fe/Cr MMLs were discussed in relation with a quantum phase transition [6], [7]. On the other hand, in order to get a better understanding the origin of GMR effect, it is worthwhile to investigate the pressure effect on GMR because the value of thickness of paramagnetic layer is easily controlled precisely and continuously by applying pressure on MML [8]. For instance, Higashihara *et al.* reported the pressure dependence of saturation field H_s is dominated mainly by the pressure change of the antiferromagnetic interlayer coupling J [9]. However, there have been few data about the quantitative comparison of pressure dependent magnetoresistance (MR) of Fe/Cr MMLs with antiferromagnetic coupling (AF) state and that with ferromagnetic coupling (F) state.

In the present work, we achieved the further refinement of sample preparation, e.g., ultrahigh vacuum and surface treatment of the substrate. We obtained consequently AF-Fe/Cr MML having large GMR in comparison with our previous study [8]. Using these Fe/Cr MMLs, we have examined the difference between the effect of pressure on the MR of Fe/Cr MML with AF state and that with F state. Besides, we investigated the difference between the pressure-dependent MR for polycrystalline AF-Fe/Cr MML and that for epitaxial one [9] at higher pressure than 1.6 GPa [8]. The pressure dependence of MR and H_s are extracted from the present data and discussed on the basis of phenomenological theory.

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II. EXPERIMENTAL PROCEDURE

A. Sample Preparation

Fe/Cr MMLs were deposited on the Si (111) single-crystal substrate via Cr buffer layer (100 Å in thickness) using dc-magnetron sputtering method in base pressure of about 8×10^{-8} Pa. Surface of Si substrate was cleaned by dilute hydrogen fluorite before deposition of Cr buffer layer. The working gas of deposition was argon and a pressure was controlled between 1.15×10^{-2} and 1.17×10^{-2} Pa. The targets are Fe(99.9% in purity) and Cr(99.9% in purity) metals. The reception number of stacking layers was 20. The results of X-ray analysis confirm that the prepared samples are polycrystalline.

B. Measurement of Electrical Resistivity

The electrical resistance was measured by a standard dc four-probe method with the current direction in the film plane. The direction of applied magnetic field is parallel to the film plane. The applied magnetic field $H(\mathrm{T})$ was between -2 T and 2 T using superconducting magnets. The MR ratio is defined as the ratio, $\Delta\rho/\rho_s = (\rho(H) - \rho_s)/\rho_s$, where ρ_s and $\rho(H)$ are the electrical resistivities above and below H_s.

C. High-Pressure Apparatus

High pressure up to 2.5 GPa was generated using a piston-cylinder apparatus utilizing the conventional Teflon-cell technique. The pressure inside the Teflon-cell was kept constant by controlling the load of hydraulic press. We used a mixture of Fluorinert FC70 and FC77 for pressure medium. The temperature inside the cell was measured by a calibrated Au(Fe)-chromel thermocouple. The details of high-pressure apparatus and method were reported previously [10].

III. RESULTS

A. Cr Thickness Dependence of GMR

Fig. 1 shows the maximum values of MR ratio $(\Delta\rho/\rho_s)_{\max}$ as a function of Cr thickness t_{Cr} for [Fe(20 Å)/Cr(t_{Cr}Å)]$_{20}$ MML.

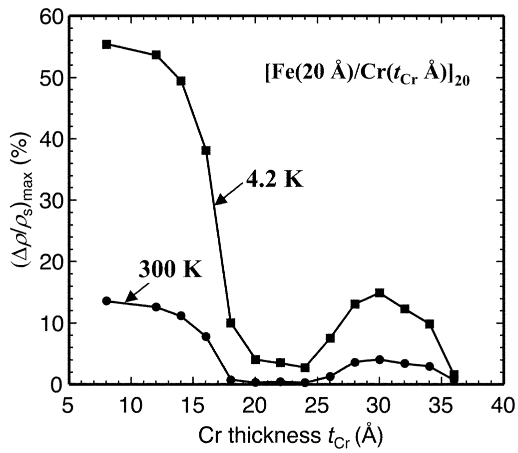

Fig. 1. Maximum values of MR ratio $(\Delta\rho/\rho_s)_{\max}$ at 4.2 and 300 K as a function of $t_{\rm Cr}$ for [Fe(20 Å)/Cr($t_{\rm Cr}$Å)]$_{20}$ MMLs.

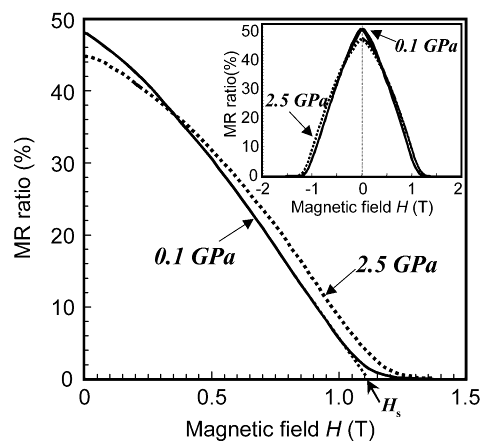

Fig. 2. MR ratio $\Delta\rho/\rho_s$ at 4.2 K of [Fe(20 Å)/Cr(10 Å)]$_{20}$ MML at 0.1 and 2.5 GPa as a function of magnetic field.

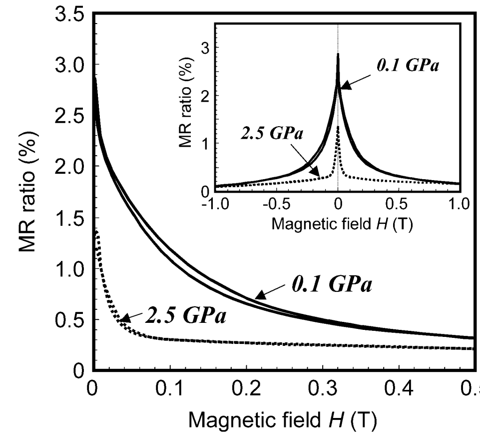

Fig. 3. MR ratio $\Delta\rho/\rho_s$ at 4.2 K of [Fe(20 Å)/Cr(22 Å)]$_{20}$ MML at 0.1 and 2.5 GPa as a function of magnetic field.

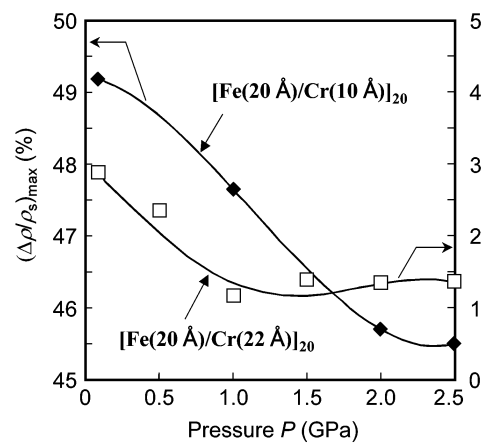

Fig. 4. Pressure dependence of $(\Delta\rho/\rho_s)_{\max}$ as a function of pressure for [Fe(20 Å)/Cr(10 Å)]$_{20}$ and [Fe(20 Å)/Cr(22Å)]$_{20}$ MML.

$(\Delta\rho/\rho_s)_{\max}$ at 4.2 K is larger than that at 300 K and oscillates with $t_{\rm Cr}$, in which the first and second peak are observed near $t_{\rm Cr} \sim 10$Å and $t_{\rm Cr} \sim 30$Å. Fe/Cr MMLs on the 1st and 2nd peak are in the AF state. On the other hand, Fe/Cr MMLs having $(\Delta\rho/\rho_s)_{\max}$ between first and second peak are F state. In this paper, "[Fe(20 Å)/Cr($t_{\rm Cr}$Å)]$_{20}$ multilayers" is abbreviated to "Fe/Cr($t_{\rm Cr}$)."

B. Effect of Pressure on MR

Fig. 2 shows the MR curves at 4.2 K of AF-Fe/Cr(10) on the first peak at 0.1 and 2.5 GPa. MR curve is symmetrical against $\pm H$ and the hysteresis is very small. It is easily seen that there are differences in the magnitude of MR ratio and H_s between 0.1 and 2.5 GPa.

$(\Delta\rho/\rho_s)_{\max}$ at 2.5 GPa is slightly smaller than that at 0.1 GPa, while H_s at 2.5 GPa is larger than that at 0.1 GPa.

Furthermore we have investigated the MR for F-Fe/Cr (22) under pressure in detail in order to make clear the difference between the pressure dependent MR of F-Fe/Cr MML and that of AF-Fe/Cr one. MR curves at 4.2 K of F-Fe/Cr(22) at 0.1 and 2.5 GPa are shown in Fig. 3. MR of this MML is due to anisotropic magnetoresistance effect (AMR) since $(\Delta\rho/\rho_s)_{\max}$ of Fe/Cr(22) is very small 2.9% at ambient pressure [11]. MR ratio at high pressure ($P = 2.5$ GPa) becomes smaller than that at 0.1 GPa. The pressure dependence of $(\Delta\rho/\rho_s)_{\max}$ is same as that of Fe/Cr(10) having GMR. However, the behavior of MR curve under pressure is apparently different from that of Fe/Cr(10) because the shape of MR curve is sharpening with increasing pressure for Fe/Cr(22).

Fig. 4 shows $(\Delta\rho/\rho_s)_{\max}$ at 4.2 K of Fe/Cr(10) and Fe/Cr(22) as a function of pressure P. The magnitude of $(\Delta\rho/\rho_s)_{\max}$ of Fe/Cr(10) monotonously decreases between 0.1 and 2.5 GPa, which value at 2.5 GPa is about 92% of that at 0.1 GPa. The pressure dependence of MR ratio is qualitatively the same as that of our previous report for Fe/Cr MML [9].

The pressure coefficient of $(\Delta\rho/\rho_s)_{\max}$ in the range between 0.1 and 2.5 GPa is obtained to be $(1/(\Delta\rho/\rho_s)_{\max})(\partial(\Delta\rho/\rho_s)_{\max}/\partial P) = -3.3 \times 10^{-2}$ GPa^{-1} by method of least squares. For Fe/Cr(22), the magnitude of $(\Delta\rho/\rho_s)_{\max}$ decreases significantly below 1 GPa and it is about 40% of that at 0.1 GPa. The pressure coefficient of $(\Delta\rho/\rho_s)_{\max}$ is estimated to be -6.0×10^{-1} GPa^{-1} below 1.0 GPa. However, the change in MR ratio is negligibly small in the pressure range from 1.0 to 2.5 GPa. The pressure dependent $(\Delta\rho/\rho_s)_{\max}$ for Fe/Cr(22) seems like that for Fe/Cr(10) below 1.0 GPa but the fractional change in $(\Delta\rho/\rho_s)_{\max}$ of Fe/Cr(22) is larger than that of Fe/Cr(10). Furthermore, we plotted H_s

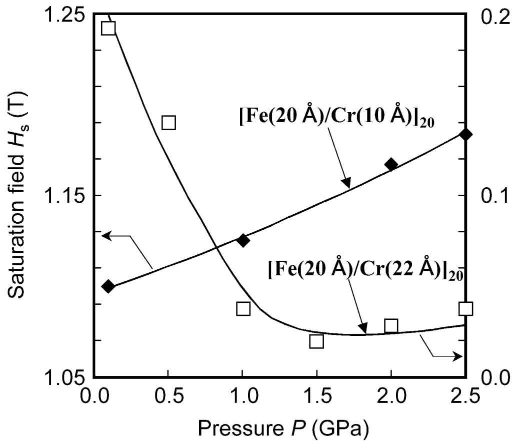

Fig. 5. Pressure dependence of H_s as a function of pressure for $[\mathrm{Fe}(20\ \text{Å})/\mathrm{Cr}(10\ \text{Å})]_{20}$ and $[\mathrm{Fe}(20\ \text{Å})/\mathrm{Cr}(22\ \text{Å})]_{20}$ MML.

versus P in order to investigate the pressure change of H_s in detail.

Fig. 5 shows H_s as a function of pressure at 4.2 K for Fe/Cr(10) and Fe/Cr(22). The value of H_s is defined as the field of intersection of the line extrapolated from the linear part of the MR curve at low field with H-axis. For Fe/Cr(10), H_s monotonously increases with increasing pressure having the pressure coefficient of $H_s, (1/H_s)(\partial H_s/\partial P) = 3.3 \times 10^{-2}$ GPa^{-1}. This behavior of H_s is qualitatively consistent with our previous result [8] although the pressure coefficients of H_s is nearly twice as the previous value.

However, the fact that H_s increases under high pressure obtained in the present work is opposite to our previous result [9], in which H_s decreases with increasing pressure. The reason for that may be due to a difference in structure between single crystal like epitaxial AF-Fe/Cr MML [12] and polycrystalline one. There are many grain boundaries in polycrystalline Fe/Cr MML. It is expected that the pressure change of grain boundaries around interfaces contributes largely to that of roughness at interfaces. The roughness at interfaces has been considered to play an important role in the shape of MR curve [13]–[15]. It is revealed that H_s increases with increasing roughness at interfaces. Considering this fact, we may assume that the application of pressure induces the roughness at interfaces in polycrystalline AF-Fe/Cr MML. In contrast, the epitaxial AF-Fe/Cr MML has atomically flat interfaces [12]. Since the epitaxial AF-Fe/Cr MML without grain boundary has homogeneous interfaces, we may postulate that the roughness at interfaces hardly changes under pressure. Thus, the pressure decrease in H_s for epitaxial AF-Fe/Cr MML cannot simply be explained by modification of roughness at interfaces. More experimental data for Fe/Cr MML having various interface structures are required to settle this point.

On the other hand, since it is difficult for F-Fe/Cr(22) to define H_s, we tentatively evaluated H_s using same method estimated for Fe/Cr(10). H_s decreases with increasing pressure up to about 1.0 GPa and the pressure coefficient of H_s is -6.8×10^{-1} GPa^{-1}. The MR for F-Fe/Cr(22) saturates easily at low field under pressure in comparison with ambient pressure: H_s at high pressure ($P > 1$ GPa) is about 0.03 T while that at ambient pressure is about 0.2 T. This result indicates that the magnetic anisotropy of F-Fe/Cr MML is sensitive to pressure and easily suppressed by applying pressure. The effect of pressure on the electron scattering due to AMR is apparently different from that due to GMR because the component of AMR is suppressed as a whole by applying pressure while the magnitude of GMR for AF-Fe/Cr(10) at high field increases slightly with increasing pressure as shown in Fig. 2.

IV. Discussion

We discuss briefly the pressure dependent H_s for AF-Fe/Cr(10) having GMR. H_s is described as $H_s = 4|J|/Mt_{\mathrm{Fe}}$, where $J(<\ 0)$ is antiferromagnetic interlayer exchange coupling, M is magnetization and t_{Fe} is thickness of ferromagnetic Fe layer [16]. By differentiating above equation with respect to pressure, we obtain the following equation:

$$\frac{1}{|J|}\frac{\partial|J|}{\partial P} = \frac{1}{H_s}\frac{\partial H_s}{\partial P} + \frac{1}{M}\frac{\partial M}{\partial P} + \frac{1}{t_{\mathrm{Fe}}}\frac{\partial t_{\mathrm{Fe}}}{\partial P}. \tag{1}$$

Since the $(1/M)(\partial M/\partial P)$ and $(1/t_{\mathrm{Fe}})(\partial t_{\mathrm{Fe}}/\partial P)$ are of the order of 10^{-3} GPa^{-1} [9], the second and third terms on the right hand side of (1) are almost negligible in comparison with $(1/H_s)(\partial H_s/\partial P)$. Thus, the pressure dependence of H_s is mainly dominated by the pressure change of the antiferromagnetic interlayer coupling $|J|$. Using result in Fig. 5, for Fe/Cr(10), the pressure coefficient of J between 0.1 and 2.5 GPa can be estimated to be $(1/|J|)(\partial|J|/\partial P) = 3 \times 10^{-2}$ GPa^{-1}. According to previous theoretical study [17], J is represented by the relation, $J = (k_{\mathrm{F}}/t_{\mathrm{Cr}})|R|^2 \sin(2k_{\mathrm{F}}t_{\mathrm{Cr}})$, where k_{F} is wave vector at Fermi level and R is the reflection probability. Effect of pressure on the J is larger than that on t_{Cr} because $(1/t_{\mathrm{Cr}})(\partial t_{\mathrm{Cr}}/\partial P) = -0.18 \times 10^{-2}$ GPa^{-1} [9]. It can be expected that the pressure increase in J is mainly due to the change of k_{F} and R rather than that of t_{Cr} under pressure.

Next, we discuss AMR under high pressure for Fe/Cr(22). The change of AMR is usually represented by $1 - (H_{\mathrm{ex}}/H_k)^2$, where H_{ex} is applied external magnetic field and H_k is anisotropy magnetic field, which corresponds to anisotropy constant. Therefore AMR decreases with decreasing anisotropy constant. In general, it is known that anisotropy constant is closely related to spin-orbit interaction. Since AMR decreases with increasing pressure, the spin-orbit interaction will be small under pressure. The reduction of spin-orbit interaction is due to the enhancement of crystal field potential caused by decrease in interatomic distance with applying pressure. From these considerations, it is suggested that the decrease in AMR is due to the decrease in anisotropy constant with weakening spin-orbit interaction under pressure.

V. Conclusion

We studied the effect of pressure on MR for AF-Fe/Cr(10) and F-Fe/Cr(22). The antiferromagnetic coupling J for Fe/Cr(10) is sensitive to pressure. It is presumed that the pressure change of J is not mainly due to decrease in t_{Cr} but the modification of electronic structure at Fermi surface. Furthermore, we reconfirmed that the pressure change of J for AF-Fe/Cr MML with polycrystalline structure is opposite to that with epitaxial one. For F-Fe/Cr(22), the component of

AMR is easily suppressed by an application of pressure. The decrease in AMR at high pressure will probably be induced by weakening spin-orbit interaction due to reduction of interatomic distance.

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